



Fermilab

**“Bo” LArTPC Cryostat  
Piping System Engineering Note**

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Date: \_\_\_\_\_

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**Piping System Engineering Note**

**Table of Contents**

1.0	Introduction.....	3
2.0	Flow schematic.....	3
3.0	Design codes and evaluation criteria.....	5
4.0	Materials .....	5
5.0	Piping design and analysis.....	5
6.0	Pressure relief system .....	15
7.0	Welding and inspection .....	16
8.0	Pressure testing.....	16
9.0	Appendix.....	17

# **“Bo” LArTPC Cryostat Piping System Engineering Note**

## **1.0 Introduction**

This document constitutes the Piping System Engineering Note for the cryogenic piping associated with the LArTPC cryostat known as “Bo” which is located inside the Proton Assembly Building at Fermilab.

The cryogenic piping transports liquid argon to the cryostat for the purpose of filling the cryostat with ultra-pure liquid argon. The pipe descriptions and a summary of the operating parameters are shown in Table 1.1.

<b>Table 1.1: Cryogenic piping description and summary</b>						
<b>Description</b>	<b>Fluid</b>	<b>OD (in)</b>	<b>ID (in)</b>	<b>P oper (psid)</b>	<b>P max (psid)</b>	<b>T (approx)</b>
“Bo” LAr supply line (vacuum jacketed)	GAr/LAr	0.500	0.430	250	400	87 K
“Bo” relief valve supply piping	GAr/LAr	1.90	1.682	10	35	87 K
“Bo” relief valve discharge vent piping	GAr/LAr	3.00	2.87	0	< 1	87 K
“Bo” cooldown/blowdown vent piping	GAr/LAr	0.500	0.430	< 15	< <350	87 K

## **2.0 Flow schematic**

The relevant portion of the flow schematic for the cryostat is shown in Figure 2.1. The complete flow schematic is available at <http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=265> in Section 1.2.

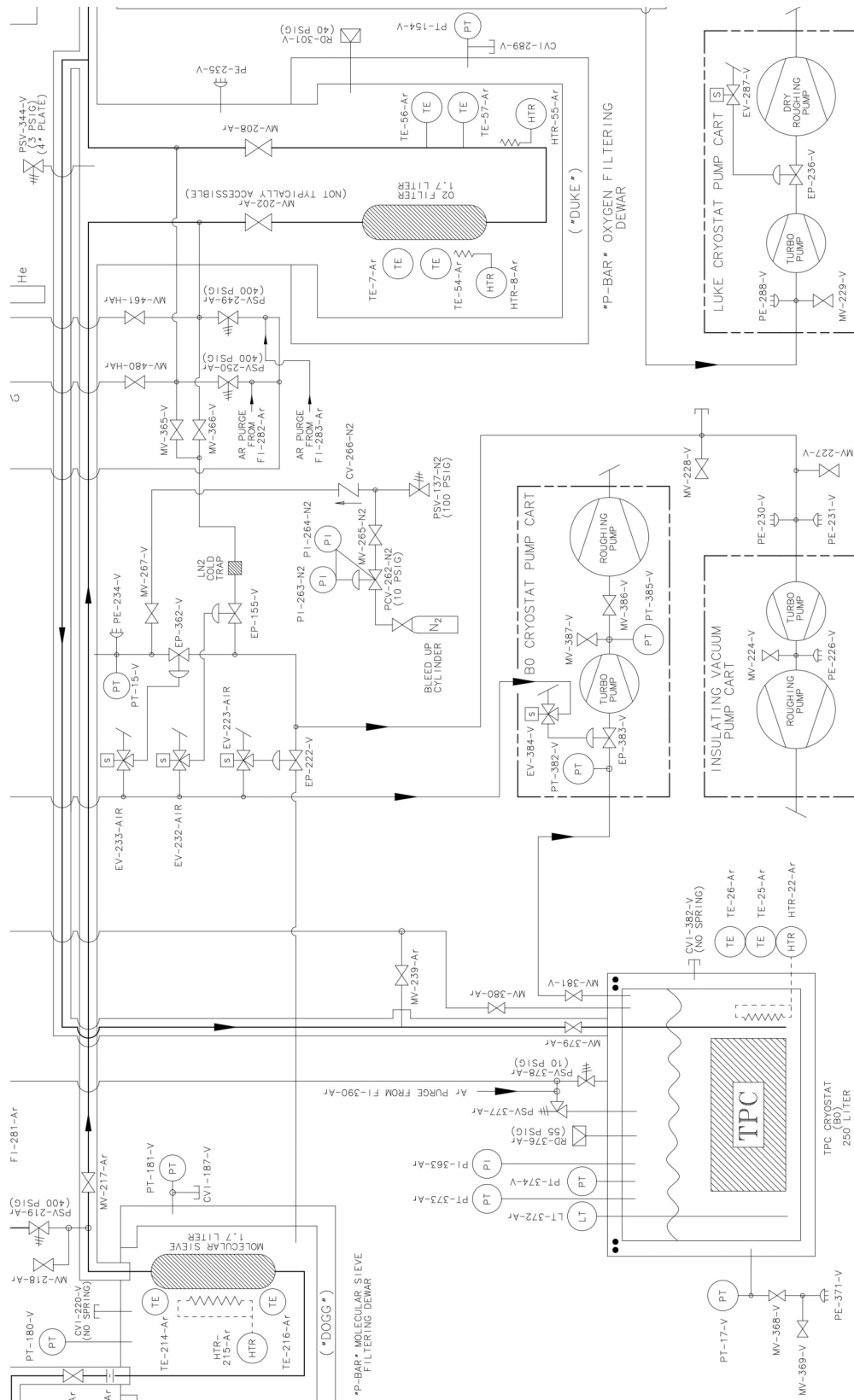


Figure 2.1 Cryostat piping flow schematic.

### **3.0 Design codes and evaluation criteria**

The “Bo” LArTPC cryostat piping must meet all of the requirements of Section 5031.1 of the Fermilab ES&H Manual. This section states that piping systems containing cryogenic fluids fall under the category of Normal Fluid Service and shall adhere to the requirements of the ASME Process Piping Code B31.3.

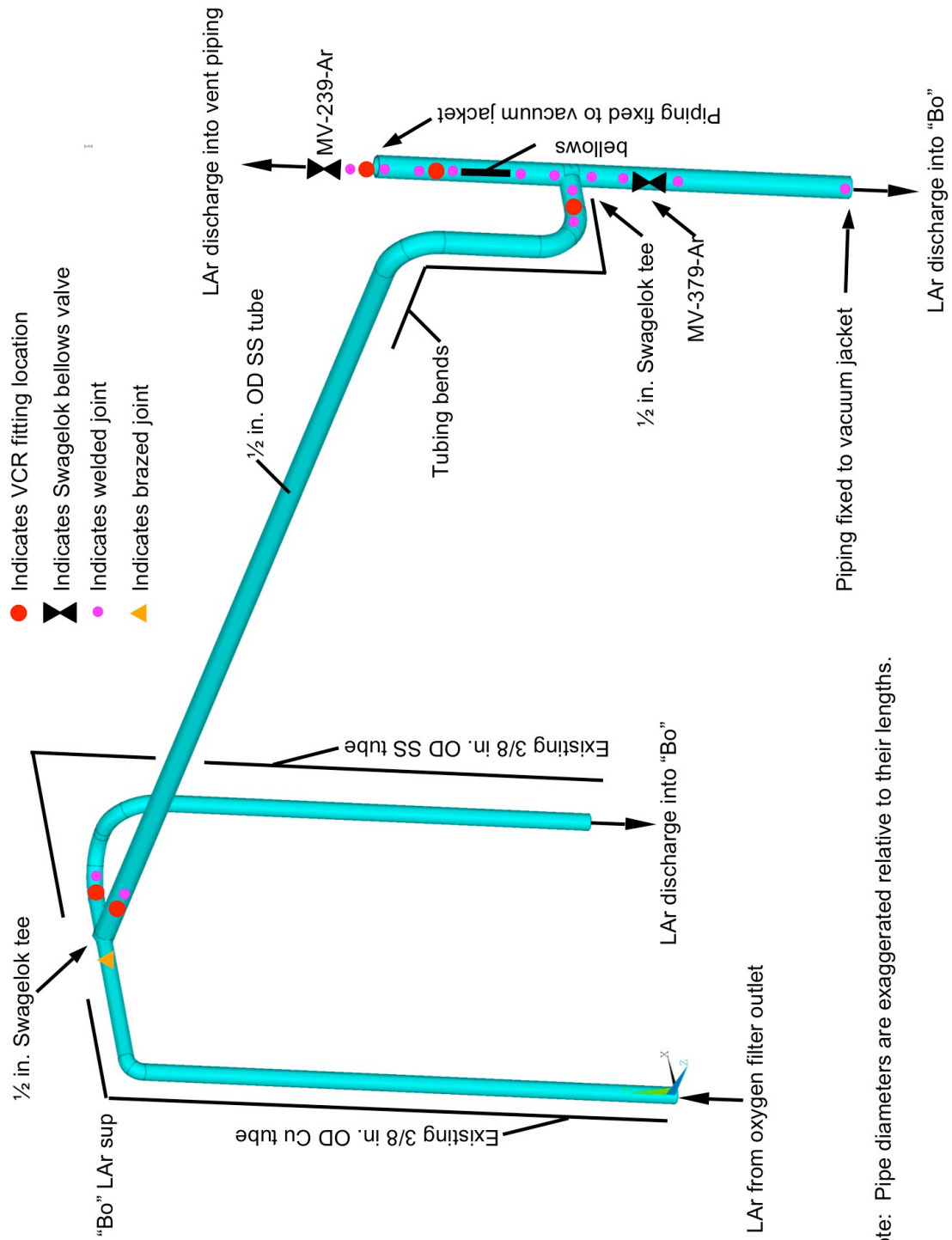
### **4.0 Materials**

The piping is fabricated from 304/304L stainless steel tube and pipe. In addition to 304/304L material, some of the components and flanges are 316/316L stainless steel. The lowest allowable stress for both of these materials from Table A-1 of ASME B31.3 will be used in this analysis, which is 16,700 psi.

The LAr piping will be operated at 87 K. This is above the minimum temperature listed for 304/316 stainless steel pipe or tube (19 K). According to Table 323.2.2 of the Code, impact testing is not required for these austenitic stainless steels. However, Table 323.2.2 does require impact testing of the weld metal and heat affected zone except as stated in Table 323.2.2 Note (6) where impact testing is not required when the minimum obtainable Charpy specimen has a width along the notch of less than 2.5 mm (0.098 in). All of the pipe or tube used in the “Bo” cryostat piping system has a manufacturer’s minimum wall thickness less than 0.098 in. Therefore, impact testing is not required for this piping system. It should also be noted the Fermilab has extensive service experience using the 300 series stainless steels at liquid nitrogen temperatures.

### **5.0 Piping design and analysis**

A schematic of the piping that supplies LAr to “Bo” is shown in Figure 5.1. The cooldown/bypass vent piping associated with “Bo” is shown in Figure 5.2.



Note: Pipe diameters are exaggerated relative to their lengths.

Figure 5.1: "Bo" LAr supply line.

Note: Pipe diameters are exaggerated relative their lengths.

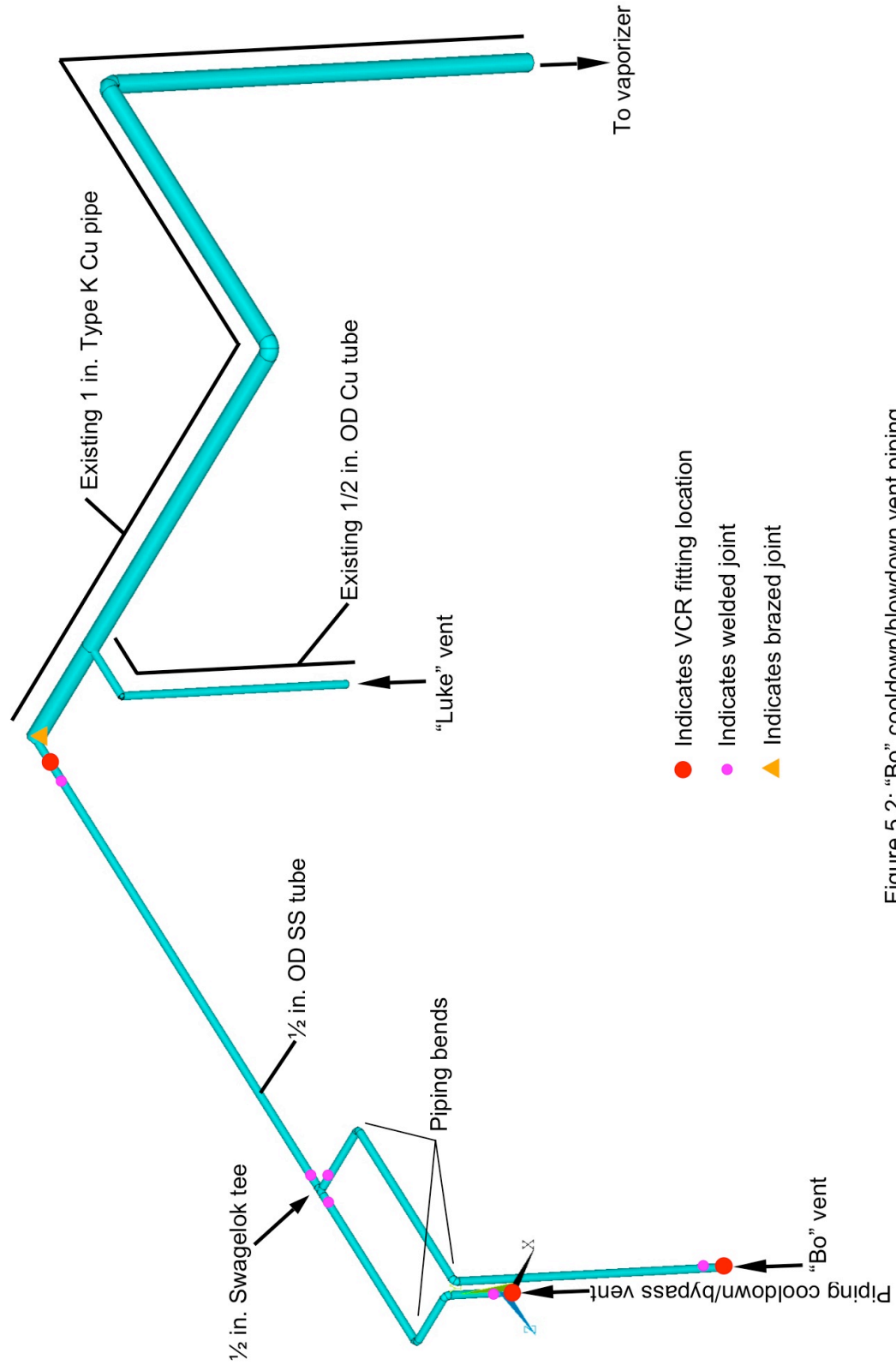


Figure 5.2: "Bo" cooldown/blowdown vent piping

The minimum thickness of the pipes is evaluated using the procedures in 304.1.2(a) of ASME B31.3. The minimum tube thickness for seamless or longitudinally welded piping for  $t < D/6$  is given by:

$$t = \frac{PD}{2(SEW + PY)}$$

where:  $t$  = wall thickness, (manufacturers minimum value is used)

$P$  = internal design pressure

$D$  = outside diameter (manufacturers nominal value is used)

$S$  = allowable stress from table A-1

$E$  = quality factor from table A-1A or A-1B = 0.8 (worst case)

$W$  = weld joint strength reduction factor = 1

$Y$  = coefficient from Table 304.1.1 = 0.4

Table 5.1 summarizes the results of the wall thickness calculation.

<b>Table 5.1. Cryogenic piping parameters</b>							
<b>Pipe / Tube</b>	<b><math>P</math> (psid)</b>	<b><math>D</math> (in)</b>	<b><math>S</math> (psi)</b>	<b><math>E</math></b>	<b><math>t</math> req'd (in)</b>	<b><math>t</math> mfg min (in)</b>	<b>MAWP (psid)</b>
LAr supply line (vacuum jacketed)	400 <sup>a</sup>	0.500	16,700	0.8	0.00740	0.0315	1772
“Bo” relief valve supply piping	35 <sup>b</sup>	1.900	16,700	0.8	0.00249	0.0954	1397
“Bo” relief valve discharge piping	< 1 <sup>c</sup>	3	16,700	0.8	0.0001	0.0585	529
“Bo” cooldown/blowdown vent piping	<< 350 <sup>d</sup>	0.500	16,700	0.8	0.0065	0.0315	1772

(a) Pressure limited by trapped volume relief valve (PSV-250-Ar).

(b) Pressure limited by cryostat ASME relief valve (PSV-377-Ar).

(c) Relief valve calculations estimate vent pressure drop as less than 1 psi

(<http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=265>, Section 4.1a).

(d) Supply dewer reliefs are set at 350 psig. The pressure in the cooldown/blowdown vent pipe during system cooldown (when the cryostat is bypassed) will be much less than 350 psig because 98% of the flow resistance is upstream of the vent pipe. The resistance coefficient for the supply piping up to the



cooldown/blowdown vent piping is 340.9 while the resistance coefficient for the vent piping is only 4.3 (all piping converted to a common reference diameter).

In the above four cases the manufacturer's minimum wall thickness of the piping is greater than the minimum thickness required by ASME B31.3.

The unlisted components installed in the "Bo" cryostat piping system as defined in B31.3 Section 304.7.2 are shown in Table 5.2.

<b>Table 5.2. Unlisted piping components.</b>				
<i>Component</i>	<i>Source</i>	<i>Pressure rating [psi]</i>	<i>System Design Pressure (psid)</i>	<i>Comment</i>
Union Tee, 0.50 in OD x 0.049 wall, 316L S.S.	Swagelok, 316L-8TB7-3	3,700 <sup>a</sup>	400	----
Union Tee	Swagelok, SS-8-VCR-T	4,300 <sup>a</sup>	400	----
Reducing Union, 0.50 in. OD x 0.049 wall, 316L S.S.	Swagelok, 316L-8TB7-6-6	3,300 <sup>a</sup>	400	----
VCR gland	Swagelok, SS-8-VCR-3	3,000 <sup>a</sup>	400	304.7.2(a) Extensive service experience <sup>c</sup>
VCR body	Swagelok, SS-8-VCR-4	3,000 <sup>a</sup>	400	304.7.2(a) Extensive service experience <sup>c</sup>
Bellows Sealed Valve	Swagelok, SS-8BG-V47	1,000	400	304.7.2(a) Extensive service experience <sup>c</sup>
Bellows Sealed Valve	Swagelok, SS-8BG-TW	1,000	400	304.7.2(a) Extensive service experience <sup>c</sup>
Bellows	X	X	X	X
Conflat flange, 2 ¾ in.	Lesker	vacuum <sup>b</sup>	35	304.7.2(a) Extensive service experience <sup>c</sup>
Reducing Union	FNAL	See Figure 5.1 and 5.3 and associated discussion.		

- (a) Swagelok literature states that the fitting pressure ratings are based on an allowable stress value of 20,000 psi in accordance with B31.3 (calculated at room temperature).
- (b) During the pressure test of the TPC signal feed thru flange (section 3.5j of the system cryogenic safety report - <http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=265>), a 2 ¾ in. conflat flange was part of the test setup. This test pressurized the 2 ¾ in. conflat to 400 psig without leakage. Thus the conflat was proof tested to > 3x the maximum operating pressure it will see per 304.7.2(c).
- (c) These components have performed satisfactorily during several transfer of liquid argon to "Luke."

The piping bends are analyzed based on 304.2.1 of the Code. The minimum required thickness is given by:

$$t = \frac{PD}{2((SEW/I) + PY)}$$

where:  $t$  = wall thickness

$P$  = internal design pressure, 400 psid

$D$  = outside diameter, 0.50 in.

$S$  = allowable stress from table A-1, 16,700 psi for 304 S.S.

$E$  = quality factor from table A-1A or A-1B = 0.8 (worst case)

$W$  = weld joint strength reduction factor = 1

$Y$  = coefficient from Table 304.1.1 = 0.4

$I$  = factor for location in pipe bend: intrados, extrados and centerline

The following equations are used to determine  $I$  at the three locations:

at the intrados: 
$$I = \frac{4(R_1 / D) - 1}{4(R_1 / D) - 2}$$

at the extrados: 
$$I = \frac{4(R_1 / D) + 1}{4(R_1 / D) + 2}$$

at the centerline: 
$$I = 1.0$$

$R_1$  = bend radius of the tubing, 5.0 in.

The results are as follows:  $t(\text{in})$  at intrados = 0.00760; extrados = 0.00722; centerline = 0.00740 (same as straight tube).

The bent tubing has a minimum wall thickness of 0.0315 inches so this requirement is satisfied.

The transition between the ½ inch SS 316L tee and the 3/8 in. OD Cu tube was fabricated from a Swagelok VCR tee (SS-8-VCR-T) as shown in Figure 5.3. Two sides of the tee are used to make up VCR joints that feed “Luke” and “Bo.” The third side of the tee had the VCR threads cut off and has a copper line brazed into it. Because the inside diameter of the tee is larger than the 3/8 in Cu tube OD, a Cu spacer was machined to create a tight

fit for brazing. The joint was brazed by Cary Kendziora using XUPER 1020 XFC silver brazing alloy which has a tensile strength of 85 ksi (data sheet included in the appendix).

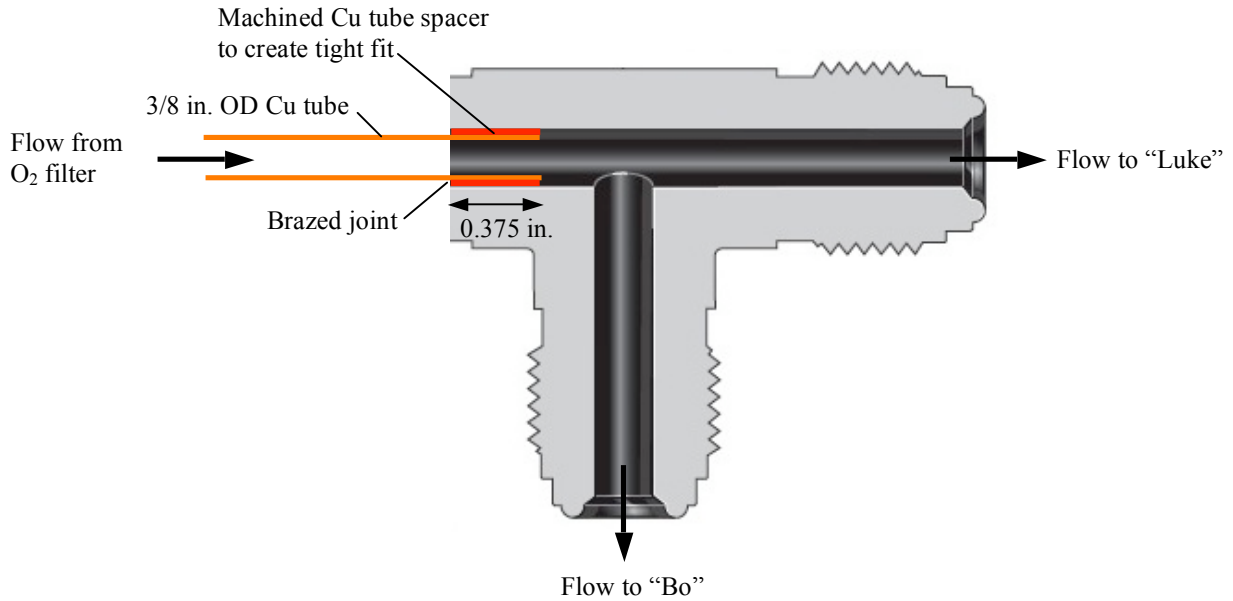


Figure 5.3: Brazed joint details

The flexibility of the LAr supply piping was analyzed using ANSYS. The model boundary conditions and results are summarized in Figures 5.4 and 5.5.

The thermal shrinkage was taken to be  $290 \times 10^{-5} \Delta L/L$  for 304 Stainless and  $314 \times 10^{-5} \Delta L/L$  for Cu tube. The modulus of elasticity of 304 Stainless was input as 2.07E11 Pa along with a Poisson's Ratio of 0.28. The modulus of elasticity of Cu was input as 1.207E11 Pa along with a Poisson's Ratio of 0.35. The model also considers the density of the contained fluid, which was input as 1400 kg/m<sup>3</sup> for argon.

The model is comprised of ANSYS PIPE 16 (straight), PIPE 17 (tee), and PIPE 18 (elbow) elements in which ANSYS calculates flexibility and stress intensification per B31.1. The stress intensification factors for B31.3 are the same as for B31.1.

The model contour plot shows a peak Von Mises stress of 2,161 psi where the 1/2 inch OD stainless steel tube discharges into Bo.

Per B31.3 Appendix P, the operating stress is computed using equation (P17a)

$$S_o = \sqrt{(|S_a| + S_b)^2 + 4S_t^2}$$

where the axial ( $S_a$ ), bending ( $S_b$ ), and torsional ( $S_t$ ) stresses are combined and compared to the allowable stress  $S_{oA}$  in para. P302.3.5(d) where

$S_{oA} = 1.25 f (S_c + S_h)$ .  $S_c$  is the basic allowable stress at the minimum metal temperature expected during the displacement cycle under analysis and  $S_h$  is the basic allowable stress at the maximum metal temperature expected during the displacement cycle under analysis. Both  $S_c$  and  $S_h$  were taken to be 16,700 psi. The stress reduction factor  $f$  was taken to be 1.0 because this system will see less than 1,000 cycles in its lifetime.

$$S_{oA} = 1.25 \times 1.0 \times (16,700 + 16,700) = 41,750 \text{ psi}$$

A macro (available in the appendix) was used to retrieve  $S_a$ ,  $S_b$ , and  $S_t$  from ANSYS and then compute the combined stress. The peak operating stress for this model was found to be 1,529 psi for the cold case (thermal shrinkage + 400 psid) and 1,138 for the warm case (400 psis loading only). Thus the operating stress range is only a few hundred psi and does not exceed the allowable operating stress limit.

These stresses are far below the 16,700 psi limit for the 304 SS tube or the 6,000 psi limit for copper tube.

Figure 5.5 shows the results from a FEA model of the LAr vent piping that connects “Bo” and “Luke” to the LAr vaporizer. The model considers the stress that results from the shrinkage from 300 K to 80 K (no internal pressure). The material properties are the same as those used in the LAr supply piping flexibility analysis.

The model shows a peak Von Mises stress of 3,844 psi where the ½ inch OD stainless steel vent tube connects to Luke. Equation P17a computes a peak stress of 3,666 psi. Thus the stress in the venting piping is far below the basic allowables for both the stainless steel and copper piping.

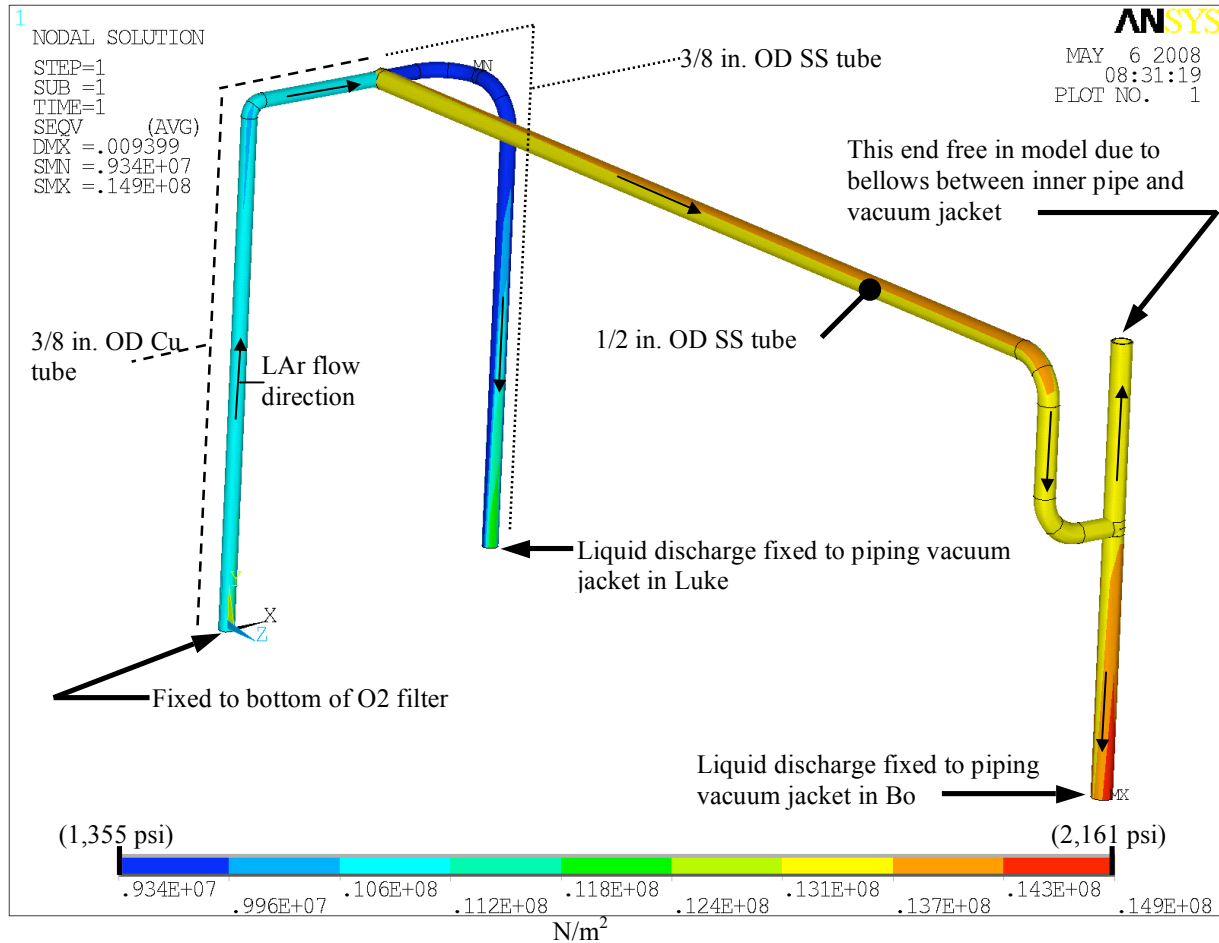


Figure 5.4: LAr supply piping Von Mises Stresses due to cooldown shrinkage and internal 400 psig pressure.

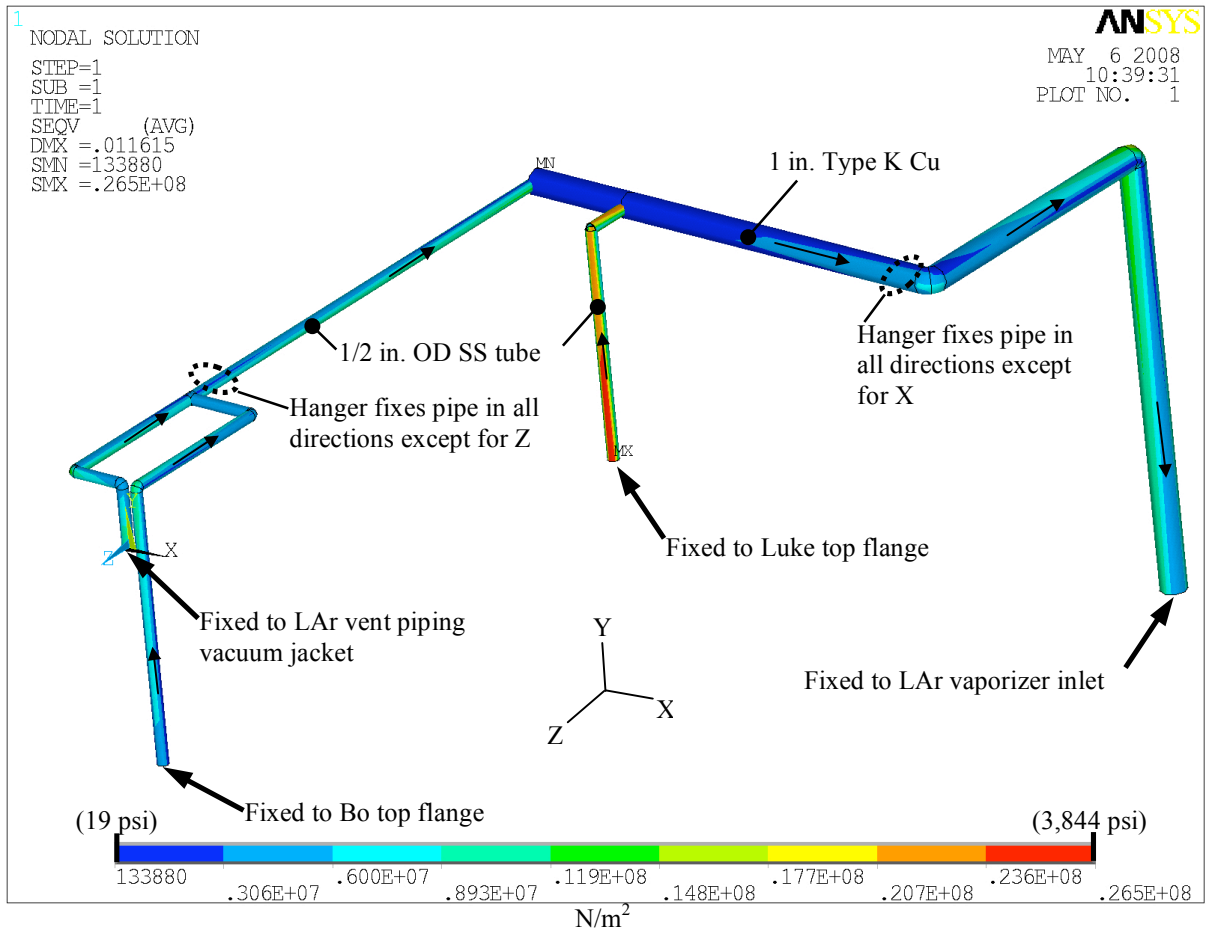


Figure 5.5: LAr vent piping Von Mises Stresses due to cooldown shrinkage.

## 6.0 Pressure relief system

The supply piping is relieved by an existing trapped volume relief PSV-250-Ar. The vent piping supplies the two cryostat relief valves, PSV-377-Ar and PSV-378-Ar.

<b>Table 7.0.1. MTF test stand relief settings.</b>		
<i>Circuit</i>	<i>Design pressure</i>	<i>Relief setting</i>
“Bo” LAr supply line (vacuum jacketed)	400 psid	385 psig
“Bo” relief valve supply piping	35 psig	35 psig & 10 psig

## 7.0 Welding and inspection

According to B31.3 Section 341, all piping in Normal Fluid Service shall be examined. Normally radiographic examination of at least 5% of the welds is required but in certain cases the use of radiographic examination is difficult or all together impossible. This is the case here where assembly techniques prevent access to specific welds for radiography. The B31.3 piping code allows the use of in-process examination in lieu of radiography on a weld-for-weld basis for these cases. The ½ inch LAr supply tubing was welded by Dan Watkins. In-process inspection was carried out by Cary Kendziora on two of these welds. There are 14 welds in the LAr supply piping, thus the 5% inspection requirement is achieved. Dan Watkins also welded the ½ inch tube vent line attached to “Bo.”

The two elbows that feed vent gas to the relief valves on “Bo” were welded by Jim O’Neill and radiographed (results available in the appendix). Jim O’Neill also welded the 3 inch OD vent line for the ASME coded and operational relief valves attached to “Bo.”

## 8.0 Pressure testing

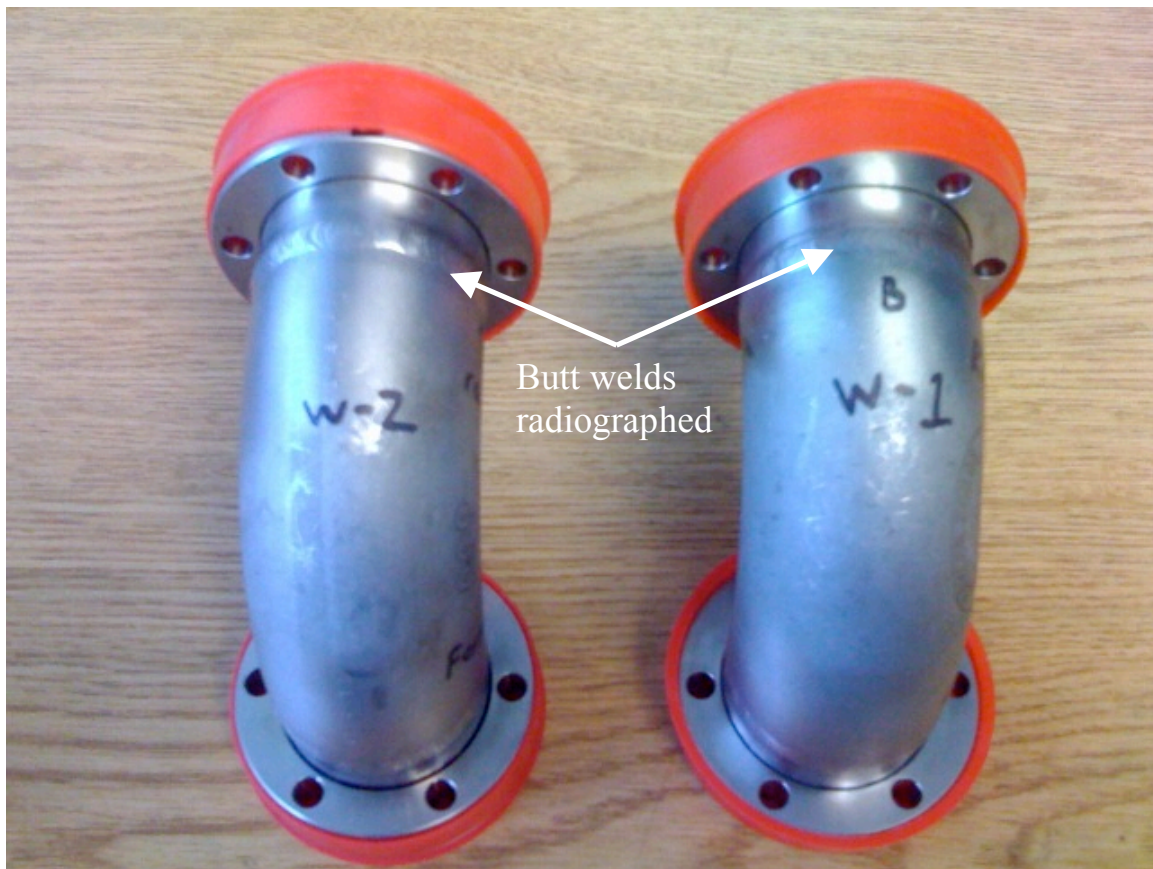
The piping system was pressure tested in accordance with Section 5034 of the Fermilab ES&H Manual and 345.5 of the Code. The test pressure is 110% of the design pressure. The test pressures was as follows:

- LAr circuit: 440 psig (while the vacuum jacket was evacuated and monitored. (See section 3.5k <http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=265>).
- Relief valve supply piping: Will be tested to 38.5 psig.

The test medium was gaseous argon.



## 9.0 Appendix



**Figure A.1: “Bo” relief valve supply elbows.**

Form: 20.1 - 212, Rev 2

Customer: <b>FERMILAB</b>		Location: <b>3640 179th HAMMOND IND.</b>		WO No.: <b>10388047</b>															
Specification: <b>ASME SEC II</b>		Acceptance Std: <b>ASME B31.3</b>		TEAM Procedure: <b>RT, ASME.I</b>															
Radiation Source Type: <input checked="" type="checkbox"/> IR-192 <input type="checkbox"/> Co-60	Source Strength: <b>70 CI</b>	Effective Focal Spot Size: <b>.119"</b>	Film to Source Distance (SFD): <b>24"</b>	Exposure Time: <b>2 min</b>															
Pipe Diameter: <b>1 1/2"</b>	Plate Thickness: <b>N/A</b>	Weld Thickness: <b>.109"</b> +Reinf.	Joint Type: <b>BUTT</b>	Material Type: <b>S/S</b>															
Penetrameter: (Type / Size) <b>ASTM 12</b>	Material Type: <b>S/S</b>	Penetrameter Location: Source Side <input checked="" type="checkbox"/> Film Side <input type="checkbox"/>	Shim Mat'l: <b>S/S</b>	Shim Thickness: <b>.065"</b>															
Film Type: <b>KODAK "T"</b>	Film Size: <b>4 1/2" X 10"</b>	Film Emulsion #: <b>211 109</b>	Film Exp.: <b>8/10</b>	Film Technique: Single <input checked="" type="checkbox"/> Multiple <input type="checkbox"/>	Film Processing: Manual <input checked="" type="checkbox"/> Automatic <input type="checkbox"/>														
Exposure Arrangement: <input type="checkbox"/> A <input type="checkbox"/> B <input type="checkbox"/> C <input checked="" type="checkbox"/> D <input type="checkbox"/> E		Intensifying Screens (Mat'l): <b>Pb</b>	Front: <b>.010"</b>	Center: <b>N/A</b>	Back: <b>.010"</b>														
<b>A</b> Single Wall - Panoramic		<b>B</b> Single Wall - Opposite		<b>C</b> Double Wall - Contact															
<b>D</b> Elliptical (0 & 90) or Superimpose (0, 120, 240)		<b>E</b> Single Wall																	
EXPOSURE NO.	WELD NO.	VIEW	"UG"	Original or Repair	ACCEPT	REJECT	Porosity	Slag or Inclusion	Tungsten Inclusion	Incomplete Fusion	Inadequate Penetration	Crack	Root Concavity	Root Convexity	Undercut	Film Artifact	Remarks	Penetrameter Density	Weld Density
	W-1	A	5.92	0	✓													2.0	2.0
		B			✓													4.0	4.0
		C			✓														
	W-2	A			✓														
		B			✓														
		C			✓														
	W-3	A			X					X									
		B			X					X									
		C			✓														
<div style="display: flex; justify-content: space-between;"> <span>Inspector: <b>CHRISTOPHER B. WOOD</b></span> <span>SIGNATURE: <i>Christopher B. Wood</i></span> <span>Level: II</span> <span>Date: <b>6/18/08</b></span> </div>																			

Figure A.2: Radiography results. Weld W-3 is a weld that is part of a different piping system that is not associated with "Bo."

```

                                post.dat
/post1
/sys, del results.res
esel,s,ename,,16

etab,sa,smisc,13
etab,sb,nmisc,90
etab,st,smisc,14

esel,s,ename,,17

etab,sa,smisc,37
etab,sb,nmisc,268
etab,st,smisc,38

esel,s,ename,,18

etab,sa,smisc,13
etab,sb,nmisc,91
etab,st,smisc,14

allsel

*get,ecnt,elem,,count ! number of elements selected
*do,qq,1,ecnt         ! loop through the elements
/gopr
*get,e1,elem,,num,min ! get starting element, lowest number

*get,ssa,elem,e1,etab,sa
*get,ssb,elem,e1,etab,sb
*get,sst,elem,e1,etab,st

/out,results,res,,append
res_%e1%=sqrt((abs(ssa)+ssb)**2+4*sst**2)
/out

esel,u,elem,,e1
*enddo

```

Figure A-3: ANSYS macro used to compute operating stress.



# Fermilab

## WELDER QUALIFICATION TEST RECORD

Welder's Name Dan Watkins Ident. No. 25 Date 3-9-84  
Welding Process(es) GTAW Type Manual  
Test in Accordance with WPS No. 155001  
Material Spec. Spec/Grade No. SA 213T304 to Spec/Grade SA 213T304  
P No. 8 to P No. 8 Thick. .277 Dia. 6"  
Filler Metal Spec. No. SFA 5.9 Class. No. ER308 F No. 6  
Backing None  
Position 6G Weld Progression Upward  
Gas Type Argon Composition 100%  
Electrical Characteristics: Current DC Polarity Straight  
Other Qualifies up to .554" Thickness

### FOR INFORMATION ONLY

Filler Metal Diameter and Trade Name Techalloy 1/16"  
Submerged Arc Flux Trade Name N/A  
Gas Metal Arc Welding Shield Gas Trade Name N/A

### GUIDED BEND TEST RESULTS

Specimen No.	Type	Figure No.	Results
1	Face	QW 462.3a	Acceptable
2	Root	QW 462.3a	Acceptable
3	Face	QW 462.3a	Acceptable
4	Root	QW 462.3a	Acceptable

### RADIOGRAPHIC TEST RESULTS (FOR ALTERNATIVE QUALIFICATION BY RADIOGRAPHY)

Radiographic Results N/A  
Test Conducted by IFR Engineering Test No. 008-15

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code.

By: *Dan Watkins*  
Date: *4/10/84*

Figure A-4: Dan Watkin's welding qualification for stainless steel.





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WELDER QUALIFICATION TEST RECORD

Welder's Name James M. O'Neal Ident. No. 1 Date 9-16-82  
Welding Process(es) GTAW Type Manual  
Test in Accordance with WPS No. 155001  
Material Spec. Spec/Grade No. SA 213 304 to Spec/Grade SA 213 304  
P No. 8 to P No. 8 Thick. .277 Dia. 6"  
Filler Metal Spec. No. SFA 5.9 Class. No. ER 308 F No. 6  
Backing No  
Position 6G Weld Progression Up  
Gas Type Argon Composition \_\_\_\_\_  
Electrical Characteristics: Current DC Polarity Straight  
Other Thickness Range Qualified: 0.062 - 0.554

FOR INFORMATION ONLY

Filler Metal Diameter and Trade Name 1/16, 3/32 Sandvick  
Submerged Arc Flux Trade Name n/a  
Gas Metal Arc Welding Shield Gas Trade Name n/a

GUIDED BEND TEST RESULTS

Specimen No.	Type	Figure No.	Results
1	Face	QW 462.3a	Acceptable
2	Root	QW 462.3a	Acceptable
3	Face	QW 462.3a	Acceptable
4	Root	QW 462.3a	Acceptable

RADIOGRAPHIC TEST RESULTS  
(FOR ALTERNATIVE QUALIFICATION BY RADIOGRAPHY)

Radiographic Results n/a  
Test Conducted by IFR Engineering Test No. 47445

We certify that the statements in this record are correct and that the test welds were prepared, welded and tested in accordance with the requirements of Section IX of the ASME Code.

By: 

Date: 9/24/82

Figure A-5: Jame's O'Neal's welding qualifications for stainless steel.